WP6 - Design & Integration: Status

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LhARA Collaboration Meeting

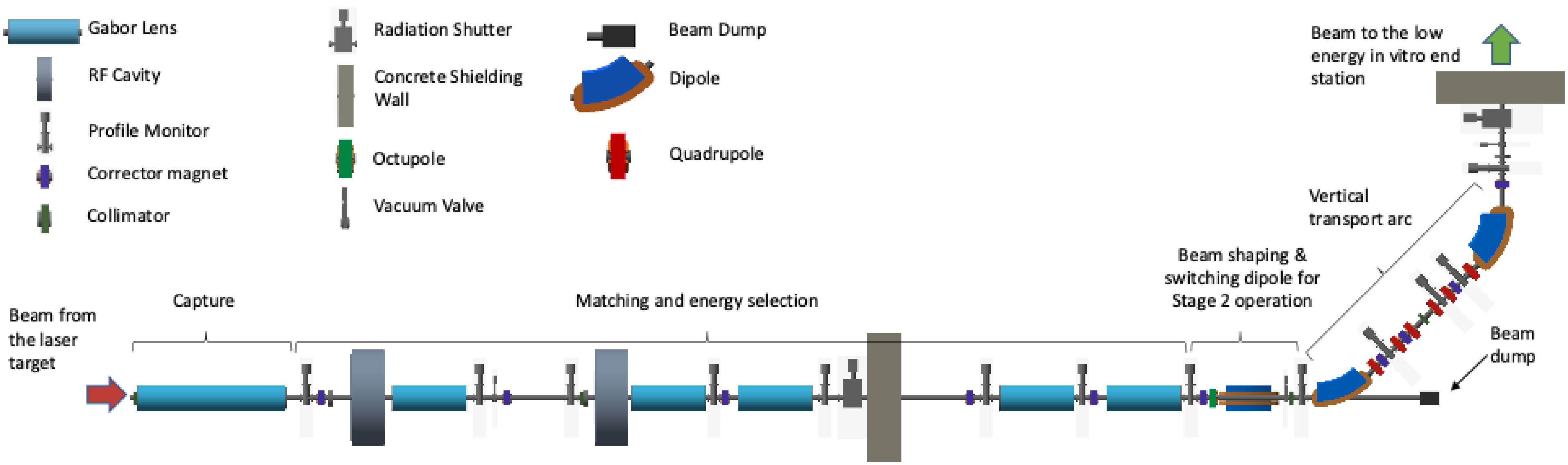
2nd September 2024

Outline

- Stage 1 update (me)
- Stage 2 FFA design update (Ta-Jen)
- Engineering & Integration (Clive)

Overview: Layout

- Locations and key dimensions defined :
  - Gabor lens
  - Arc magnets
  - RF cavities
  - Collimators
  - Corrector magnets
  - Vacuum valves
  - Wall current monitors
  - Profile monitors
  - Shielding walls
  - Radiation shutters
  - Octupole
  - Beam dump
  - Stage 2 switching magnet



Overview: Key Parameters

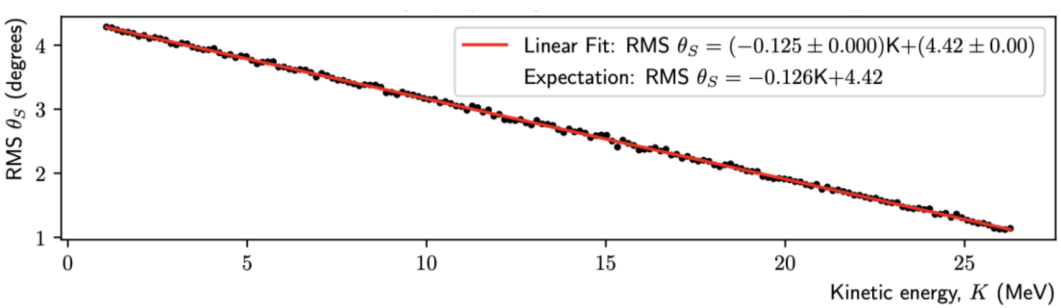
Parameter	Value/Range	Unit
Laser Parameters		
Power	100	TW
Energy	2.5	J
Pulse length	25	fs
Rep. rate	10	Hz
Proton Energy	15	MeV
Ion Energy	3.77	MeV/u
Proton & Ion Capture		
Beam Divergence at design energy	11	degrees
Gabor Lens effective length	0.857	m
Gabor Lens physical length*	1.157	m
Cathode Radius	0.0365	m
Maximum Voltage	65	kV
Number of Gabor Lenses*	2	
Alternative technology: solenoid length	1.157	m
Alternative technology: solenoid max field	1.4	T
Stage 1 Beam Transport		
Number of Gabor lenses	5	
Number of re-bunching cavities	2	
Number of collimators	2	
Arc bending angle	90	Degrees
Number of bending magnets	2	
Maximum dipole field	0.55	T
Number of quadrupoles	6	
Maximum quadrupole field	0.65	T
Number of octupoles	1	
Beam pipe radius	0.0365	m

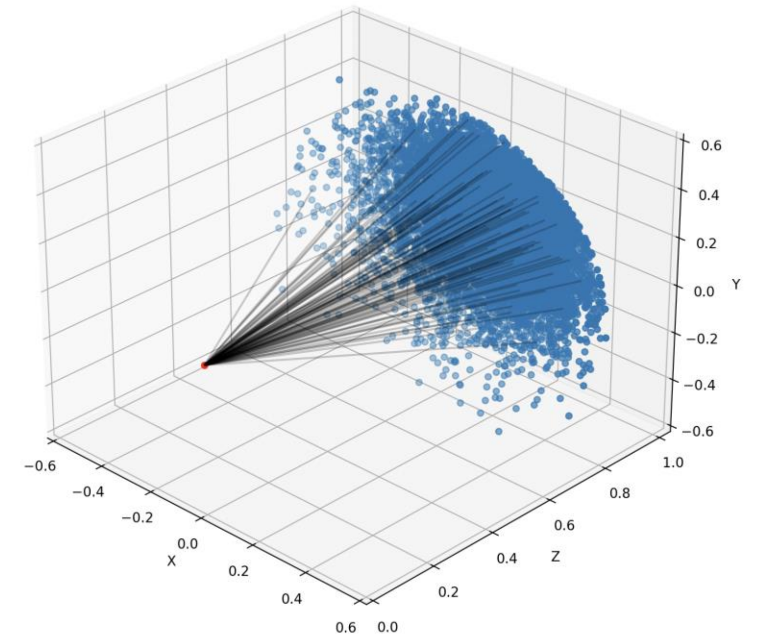
Parameterised Source Distribution

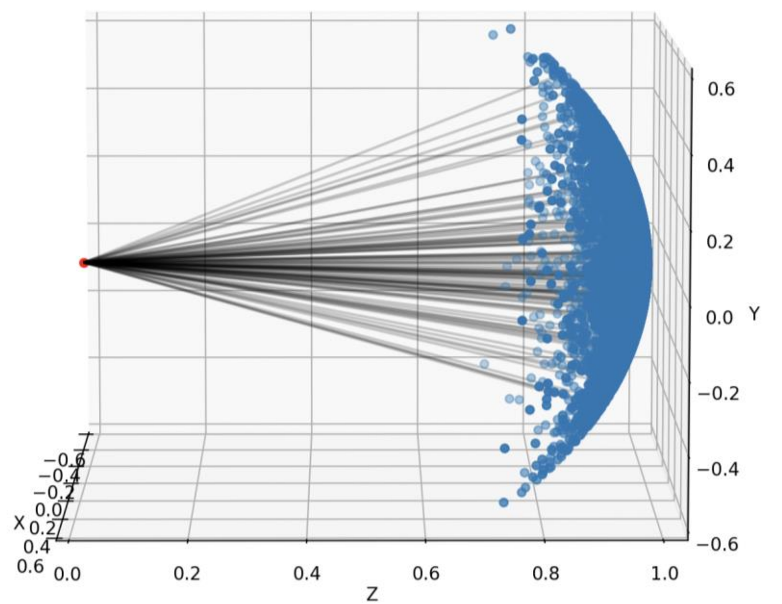
- LhARALinearOptics
  - K. Long, M. Maxouti, N. Dover
  - Code for modelling LhARA beam lines
  - Optics, losses, particle source
- Angular distribution generated as a cone centred on the normal to the foil surface.
  - The opening angle of the cone taken from:

$$\sigma_{\theta_S}(E) = 20° - 15° \frac{E}{E_{max}}$$

  - Low KE angle taken to be 20°, linearly decreases such that angle at E_{max} is 5° (based on [1]).
  - The distribution of the polar angle, θ_s, approximated as Gaussian
  - 11° at 15 MeV (25 MeV E_{max})







[1] F. Nurnberg, M. Schollmeier, et al., Review of Scientific Instruments 80 no. 3, (03, 2009) 033301

Parameterised Source Distribution

- KE spectrum from [2], unable to predict cut-off KE:

$$\frac{dN}{dE} = \frac{n_{e0} c_s t_{laser} S_{sheath}}{\sqrt{2ET_e}} \exp\left(-\sqrt{\frac{2E}{T_e}}\right)$$

- Model in [3] has cut off given by:

$$E_{max} = X^2 E_{i,\infty}$$

$$\frac{t_{laser}}{t_0} = X\left(1 + \frac{1}{2}\frac{1}{1-X^2}\right) + \frac{1}{4}\ln\left(\frac{1+X}{1-X}\right)$$

- Probability of particle generated in E -> E+dE:

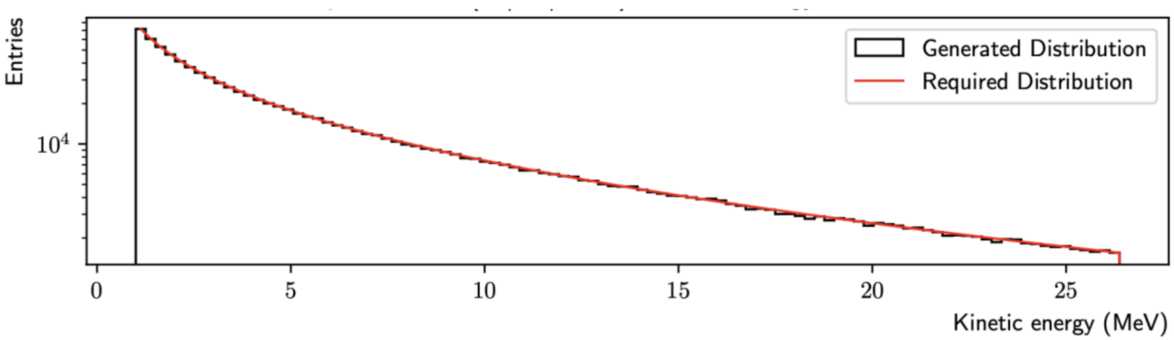
$$\delta\mathcal{P} = g(E)\,\delta E \qquad g(E) = \frac{1}{\mathcal{N}}\frac{dN}{dE}$$

$$G(E) = \int_{E_{\rm min}}^{E_{\rm max}} g(E)dE$$

$$G(E) = \frac{2}{\mathcal{N}}\frac{n_{e0} c_s t_{laser} S_{sheath}}{\sqrt{2T_e}}\sqrt{\frac{T_e}{2}}\left[\exp\left(-\sqrt{\frac{2E_{\rm min}}{T_e}}\right) - \exp\left(-\sqrt{\frac{2E}{T_e}}\right)\right]$$

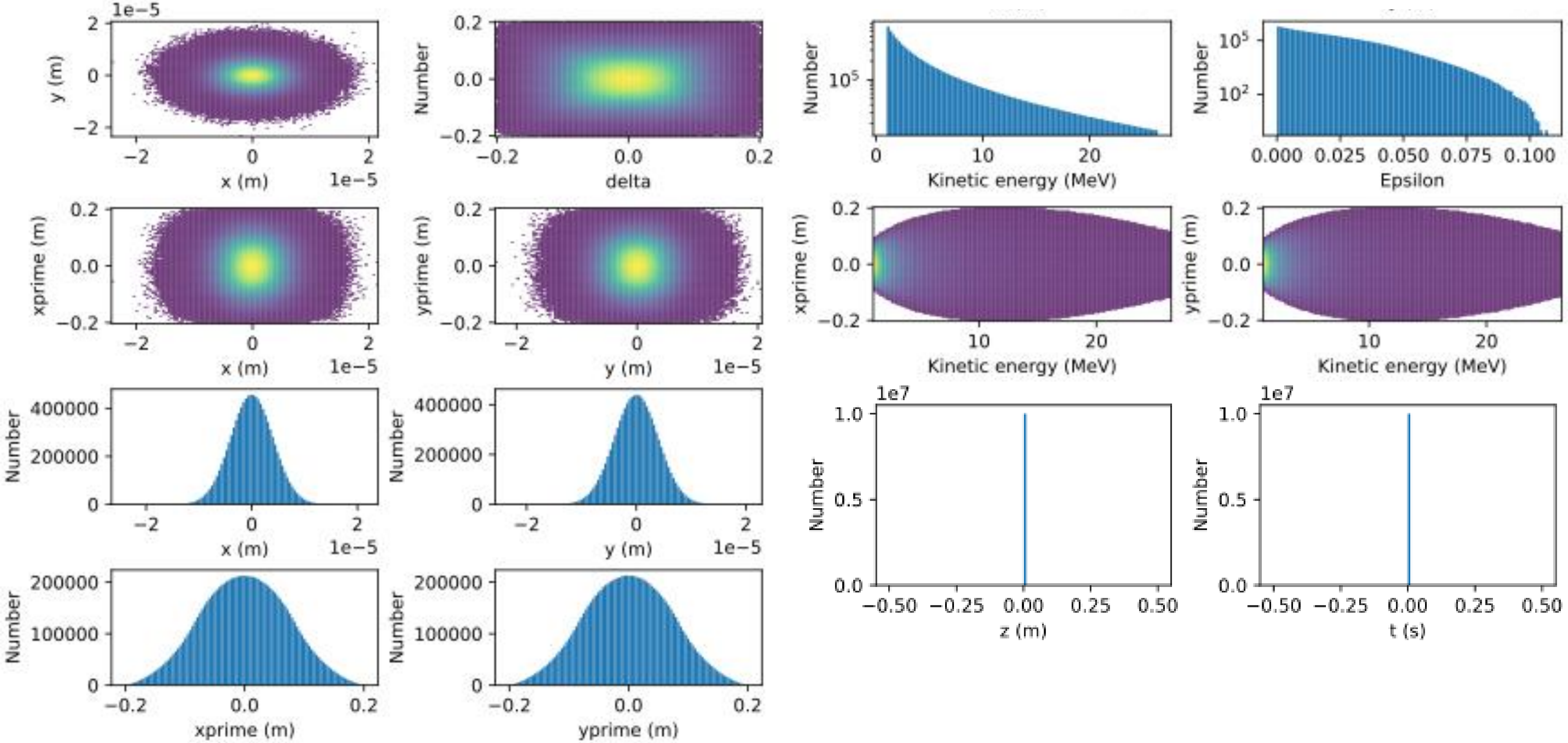
$$E = \left[\sqrt{E_{\rm min}} - \sqrt{\frac{T_e}{2}}\ln\left(1 - \frac{G(E)}{G(E_{\rm max})}\right)\right]^2$$

Parameter	Value	Unit
σ_x	4	μm
σ_y	4	μm
$\cos\theta_S\|_{\rm min}$	0.998	
$E_{\rm min}$	1.0	MeV
$E_{\rm max}$	25.0	MeV
nPnts	1000	
Laser power	2.5e-15	W
Laser energy	70.0	J
Laser wavelength	0.8	μm
Laser pulse duration	2.8e-14	s
Laser spot size	40	μm
Laser intensity	4e+20	J/m^2
Electron divergence angle	25.0	degrees
RMS θ_S at $K = 0\,$MeV	20	degrees
Scaled slope of RMS θ_S versus K	15	degrees

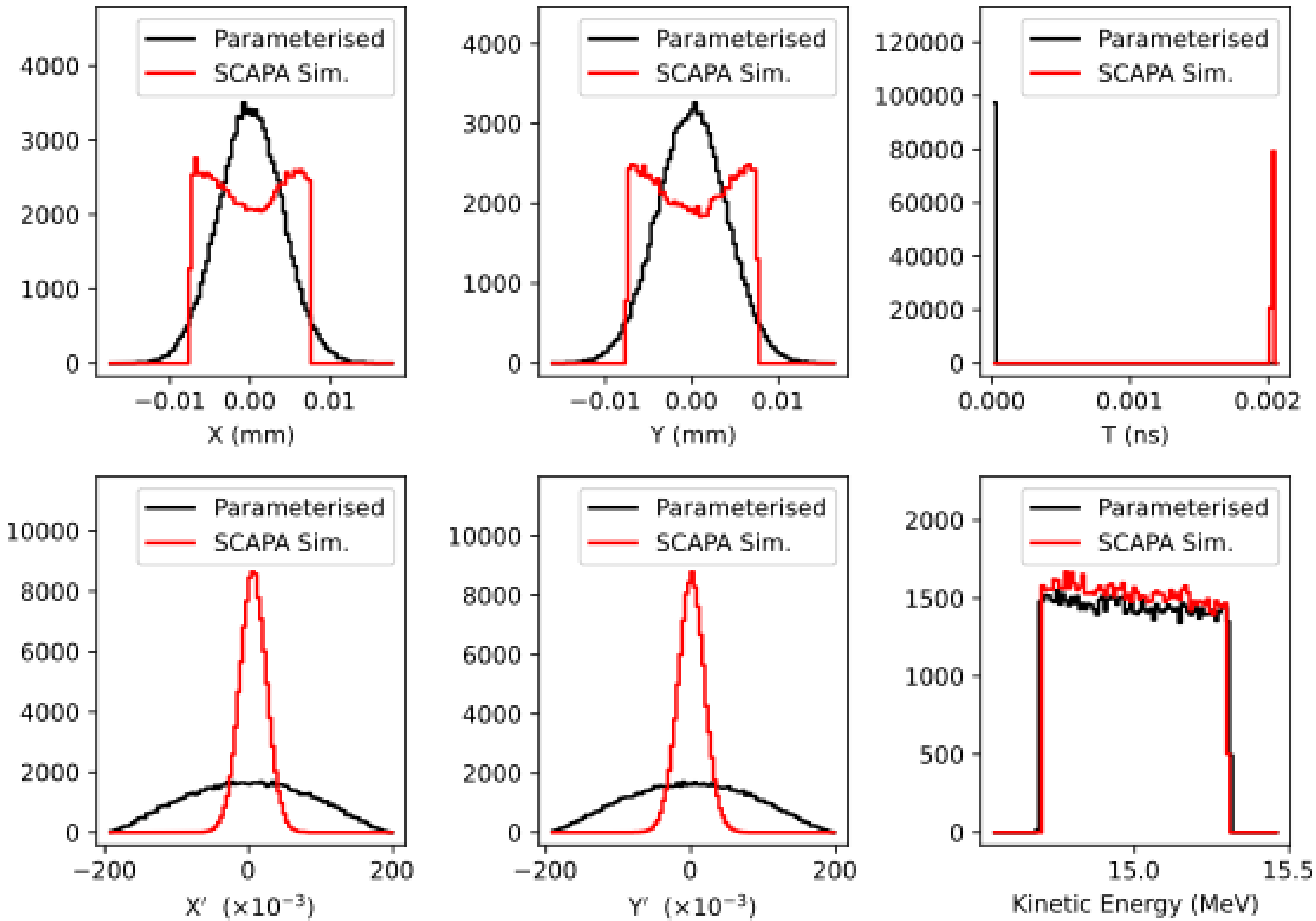


[2] J. Fuchs, P. Antici, et al.," Nature Physics 2 (01, 2006
[3] J. Schreiber, F. Bell, et al., Physical review letters 97 (08, 2006) 045005

LhARA Linear Optics

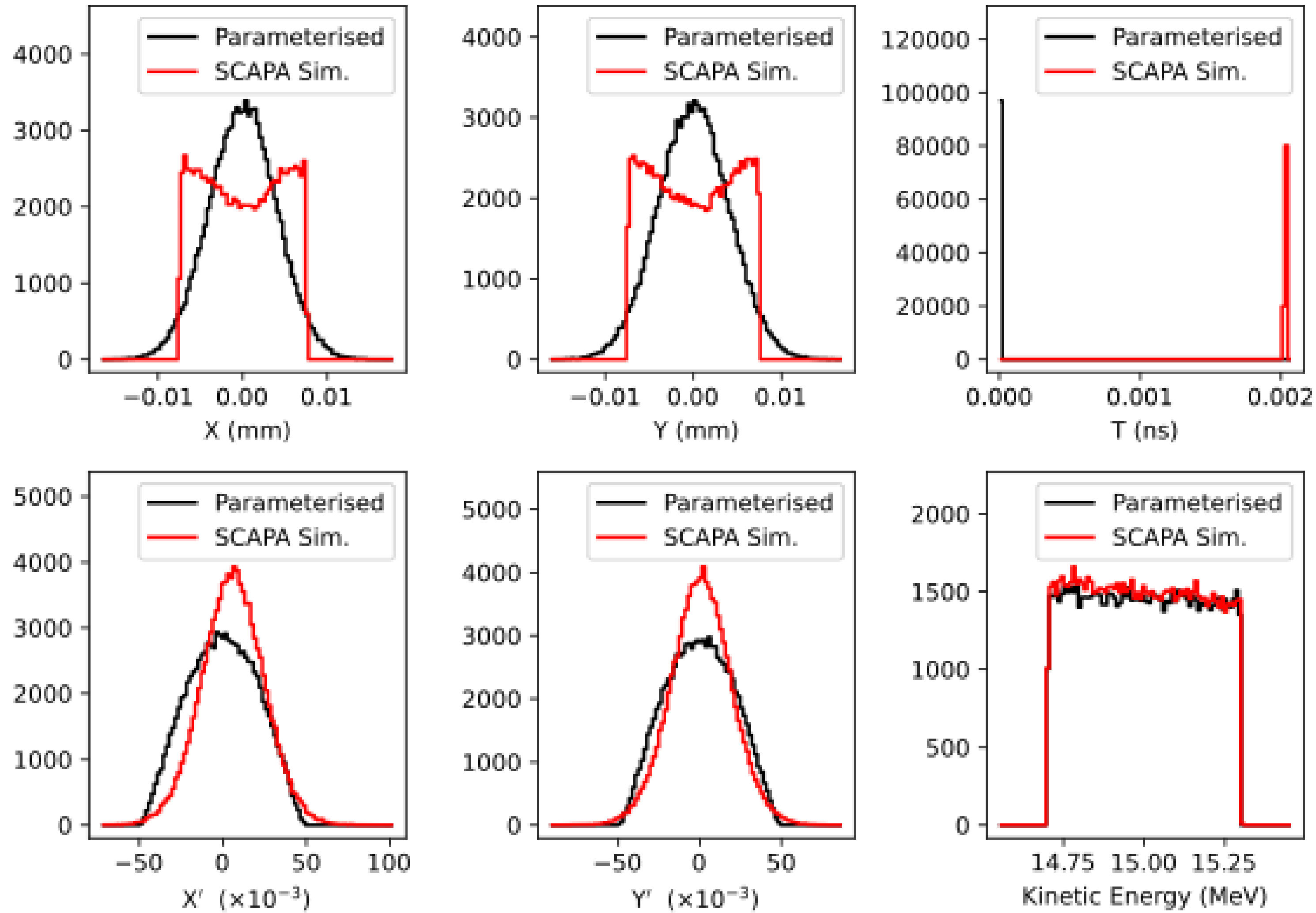


Beam Comparison To SCAPA Simulation



Reduced Divergence Comparison

- Test: theta distribution reduced by factor 4



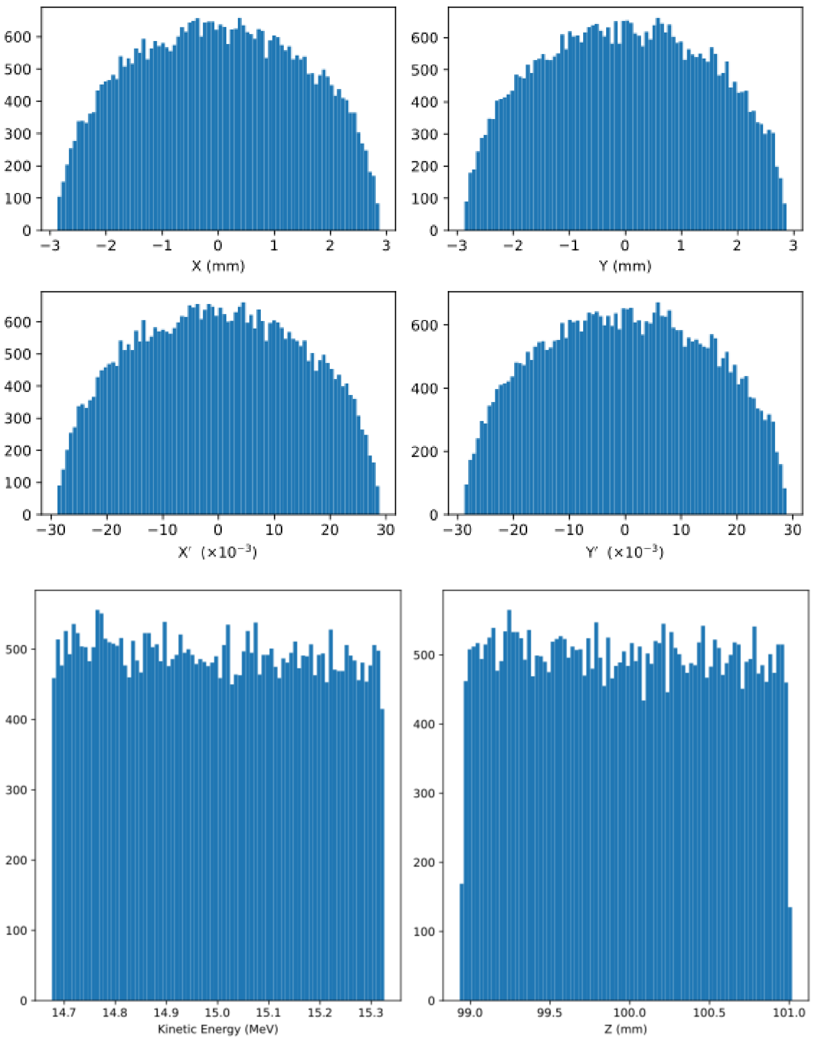
Stage 1 Nozzle

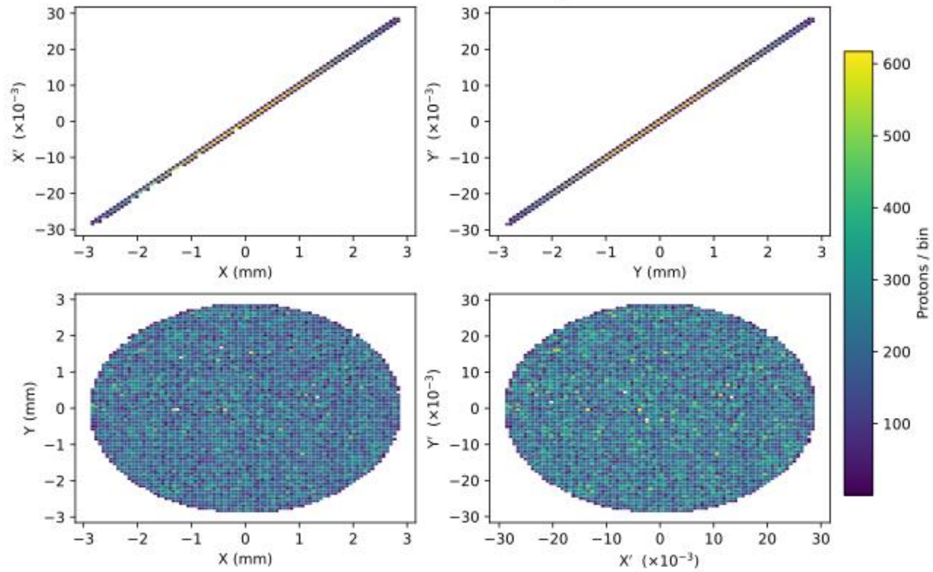
- Methodology
  - Generate beam (LLO)
  - Track 5cm
  - 2mm radial filter
  - Track 5cm with space charge
  - 2.87mm radial filter

Transmission (%)	Nozzle Entrance	Nozzle Exit
OSIRIS SCAPA Simulation,	88.7	68.0
Parameterised Beam, $\theta_s = 11°$	**7.9**	**4.1**
Parameterised Beam, $\theta_s = 2.75°$	87.5	55.9

Beam Property	OSIRIS SCAPA Simulation		Parameterised Beam, $\theta_s = 11°$		Parameterised Beam, $\theta_s = 2.75°$	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
TWISS α	-199	-209	**-355**	**-357**	-341	-342
TWISS β (m)	19.65	20.60	**35.35**	**35.51**	33.89	33.93
Emittance (m rad)	8.53e-08	8.11e-08	**5.91e-8**	**5.87e-8**	5.77e-8	5.75e-8
Beam Size (m)	1.28e-03	1.28e-03	**1.43e-3**	**1.43e-3**	1.39e-3	1.40e-3

Stage 1 Beam at the Nozzle Exit

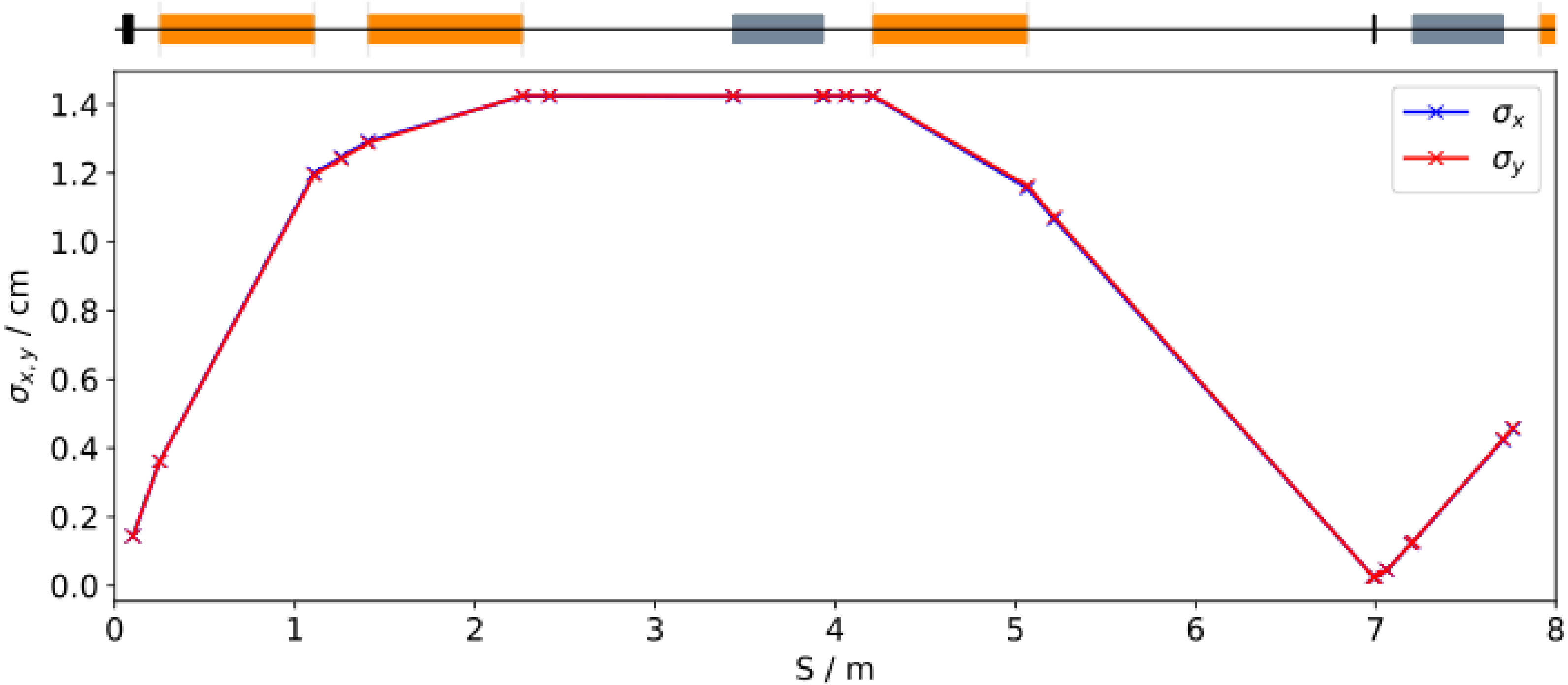




- Final 15 MeV ± 2% beam for particle tracking simulations

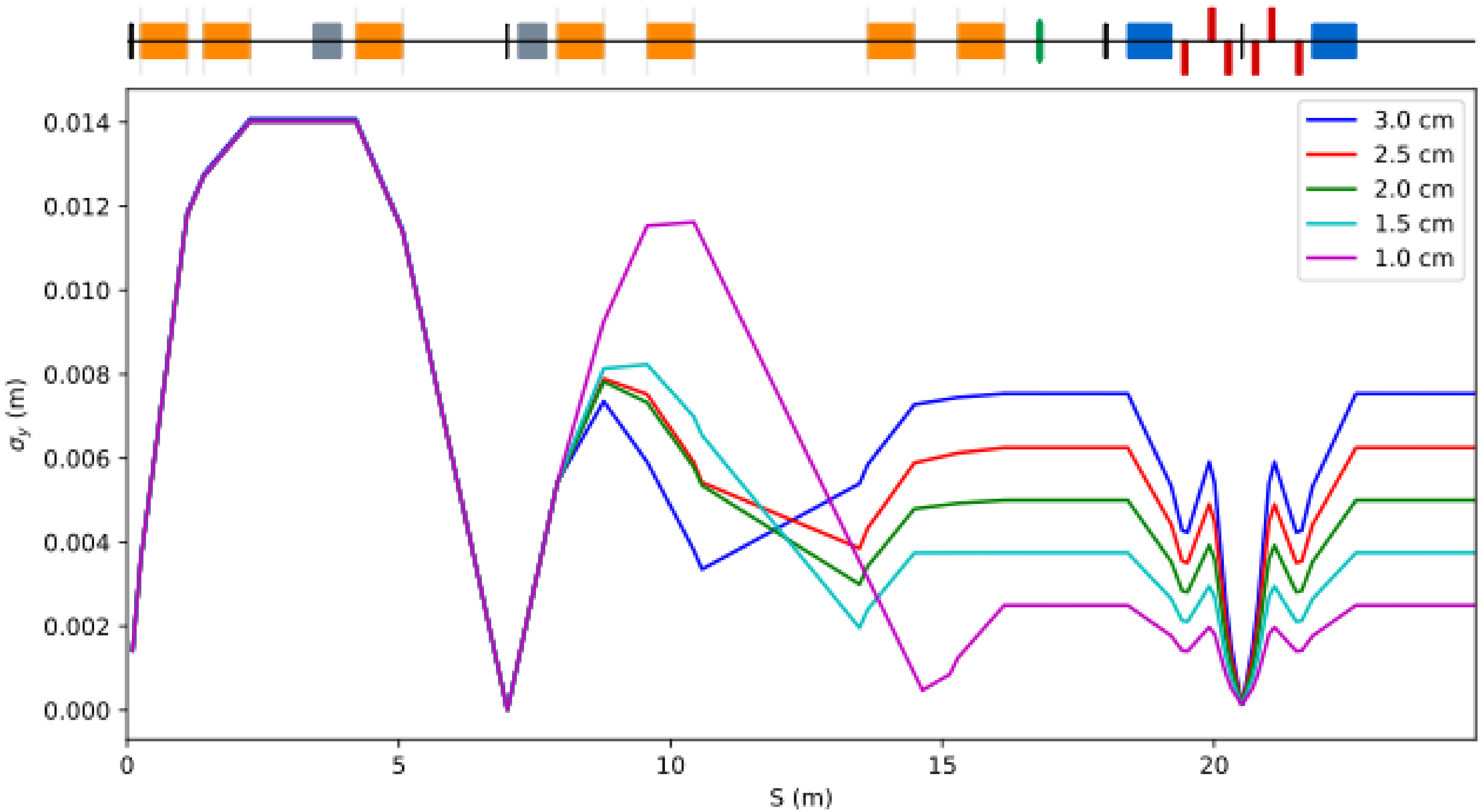
- Small differences in beam properties depending on particle count (% level)
    - Good agreement at nozzle entrance – likely a space charge effect.

Stage 1: Capture and Energy Selection



Solenoid (%)	SCAPA OSIRIS Simulation		Theta S = 11		Theta S = 2.75	
	KS (m^{-1})	B (T)	KS (m^{-1})	B (T)	KS (m^{-1})	B (T)
GL1	2.4917	1.4	2.4917	1.4	2.4917	1.4
GL2	1.0187	0.5724	1.0168	0.5713	1.0175	0.5717
GL3	1.4485	0.8138	1.4486	0.8139	1.4486	0.8139

Stage 1 Optics Flexibility



- Flexibility preserved for delivering 1-3 cm spot sizes.

Gabor Lens Strengths

Beam Size , 2 σ diameter (cm)	Solenoid 4 B Field (T)	Solenoid 5 B Field (T)	Solenoid 6 B Field (T)	Solenoid 7 B Field (T)
1.0	0.7727	0.8222	4.466e-03	1.3746
1.5	1.0893	0.7576	1.1466	0.0382
2.0	1.1654	0.7032	0.9633	0.2220
2.5	1.1491	0.7637	0.8972	0.2634
3.0	1.2804	0.6017	0.7816	0.2048

Stage 1 Optics for Stage 2 Operation

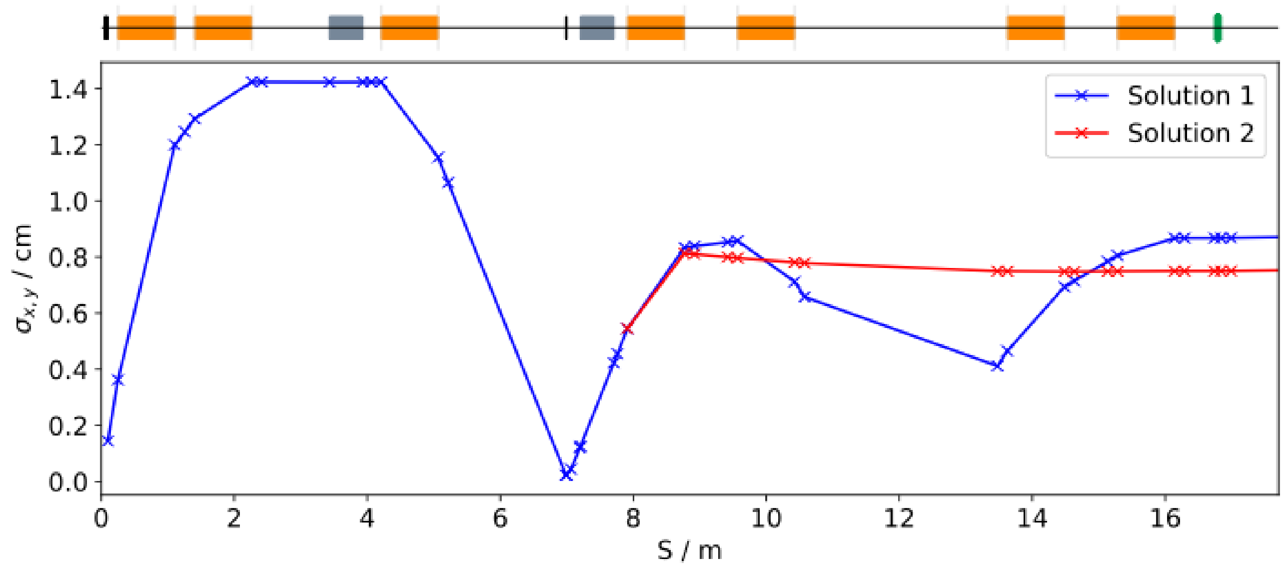
- Challenges meeting baseline injection line beam parameters
  - Emittance ~4.3e-6, beta of 50m = 1 sigma beam radius of 1.46 cm.
- Solutions prioritising alpha = 0

Solution 1:

Alpha x: -0.09
Alpha y: -0.11
Beta x: 17.92
Beta y: 18.01
Emit x: 4.30e-06
Emit y: 4.29e-06

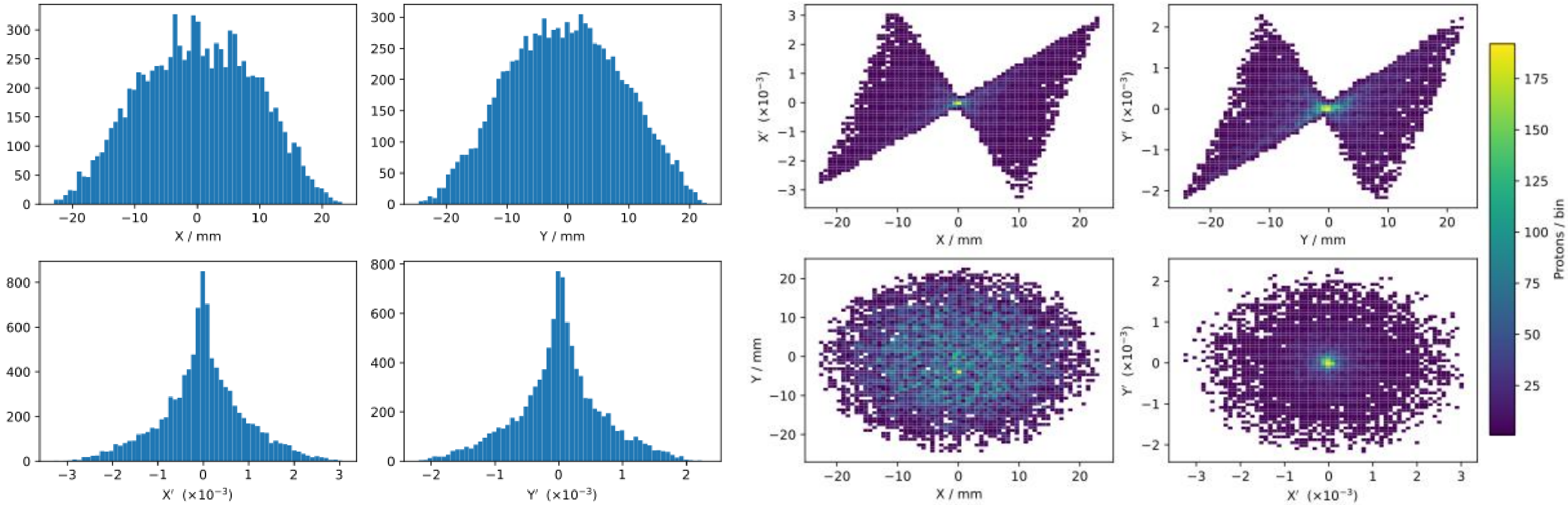
Solution 2:

Alpha x: -0.112
Alpha y: -0.169
Beta x: 17.49
Beta y: 17.37
Emit x: 3.22e-06
Emit y: 3.235e-06

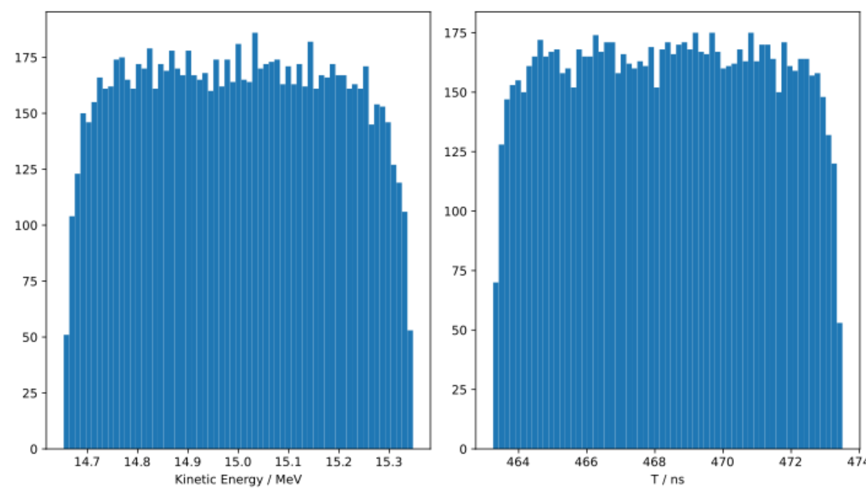


Solution	Solenoid 4 B Field (T)	Solenoid 5 B Field (T)	Solenoid 6 B Field (T)	Solenoid 7 B Field (T)
1	1.0719	0.8482	0.7448	0.4998
2	1.0976	0	0	0.1176

Beam at the Stage 1 End Station



- Symmetric, circular, parallel beam.
  - 3.6cm spot size
- Small growth in energy spread due to space charge
- Uniform spectrum and temporal profile



Summary

- Standard parameterised source developed
- Stage 1 performance unaffected
- No other stage 1 changes
- **Ready for CDR write-up.**

ROYAL HOLLOWAY UNIVERSITY OF LONDON

LhARA Laser-hybrid Accelerator for Radiobiological Applications

JAi John Adams Institute for Accelerator Science

Thank you

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